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# Shoreline change analysis in Da Nang, Vietnam, using CoastSat: A framework for assessing algal bloom risk

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**Abstract.** Coastal zones worldwide are under immense pressure from climate change and anthropogenic activities, resulting in significant shoreline dynamics. This study presents a 20-year analysis (2004–2024) of shoreline changes in Da Nang, Vietnam, using the automated open-source CoastSat library with Landsat and Sentinel-2 satellite imagery. The analysis reveals a pronounced erosional trend in the southern coastal zones, linked to rapid urban development, and mild accretion on the Son Tra Peninsula, attributed to natural processes. The primary contribution of this research is the reframing of these physical dynamics as indicators of ecological risk. Our analysis revealed shoreline retreat rates up to –6.5 m/year in the southern sections and accretion up to +4.2 m/year in the northern transects during 2004–2023. These findings suggest that development-driven erosion not only accelerates sediment redistribution but may also facilitate nutrient loading into nearshore waters. In addition, anthropogenically altered morphology, such as channel realignment and coastal construction, appears to create semi-enclosed and hydrodynamically stagnant zones. These zones, in turn, can serve as potential incubation areas for harmful algal blooms. The study therefore provides quantitative evidence that shoreline dynamics can be used as a spatial proxy for assessing ecological risks in rapidly urbanising coasts.

**Keywords:** shoreline dynamics, coastal erosion, harmful algal blooms, eutrophication, CoastSat

## 1 Introduction

The shoreline is a dynamic interface between terrestrial and marine environments, continuously shaped by natural forces and, increasingly, by anthropogenic activities. In the context of global climate change and rapid urbanisation, coastal processes such as erosion and accretion have intensified, posing significant threats to natural resources, infrastructure, and coastal communities [1]. Beyond these physical impacts, such changes often catalyse the degradation of marine ecosystems, with one of the most critical consequences being the increased frequency and intensity of harmful algal blooms (HABs) [2].

Long-term phytoplankton surveys in Da Nang's coastal waters (44 stations, 2002–2016) identified 316 taxa and 36 potentially harmful microalgal species; notably, Pseudo-nitzschia spp. exhibited higher cell densities during the northeast monsoon, providing a local baseline for HAB risk on this coastline [3]. At a broader south-central regional scale, complementary evidence shows that potentially toxic benthic dinoflagellates occur seasonally in Nha Trang Bay, with environmental drivers (temperature, salinity, PAR and nutrients) modulating bHAB dynamics; 73 dinoflagellate taxa have been documented in Xuan Dai Bay with abundances linked to surface physical parameters and bottomlayer nutrients; and 55 dinoflagellate cyst types have been reported from Van Phong Bay sediments, including cysts of toxic/bloom-forming species that may seed future HABs in semi-enclosed settings [4], [5]. Additionally, on 25 March 2018, municipal monitoring documented a ~5-km nearshore discoloration along Nguyen Tat Thanh Beach (Da Nang) and identified the dinoflagellate Tripos furca in water samples—an episodic HAB-like event that further motivates integrating shoreline-change analysis with practical HAB risk screening [6].

This study posits that shoreline change is intrinsically linked to the two fundamental conditions that foster HABs: nutrient enrichment and water column stagnation. Anthropogenic activities, particularly rapid urbanisation, land reclamation, and the construction of coastal infrastructure such as sea dikes, ports, and resorts, are the primary drivers of these conditions [6], [7], [8]. Firstly, intensified erosion, often a direct result of coastal development, serves as a major pathway for nutrient loading. It transports land-based sediment, rich in nitrogen and phosphorus from urban runoff and historical land use, into the coastal waters, thereby fueling the process of eutrophication that underpins algal growth [9]. Secondly, the physical alteration of coastal morphology—through the construction of hard structures such as seawalls and ports or through artificially induced accretion—modifies local hydrodynamics. This can create zones of poor water circulation and stagnation, which function as ideal "incubators" where algal cells can accumulate, thrive in warmer, nutrient-rich water, and proliferate into a bloom [10], [11].

While remote sensing (RS) and Geographic Information Systems (GIS) have proven highly effective for monitoring the spatio-temporal dynamics of shorelines [12], and such studies have been conducted in various regions of Vietnam, a critical gap remains in Da Nang. Previous work has not fully established a quantitative link between long-term shoreline dynamics and the emergent risk of ecological hazards like HABs. This research aims to address that gap. It moves beyond a conventional shoreline mapping exercise to reframe the analysis as a diagnostic tool for ecological risk assessment.

The primary objective of this study is to utilise the quantified shoreline changes along the Da Nang coast from 2004 to 2024 as a spatial proxy to identify and map the areas most vulnerable to harmful algal blooms. Specifically, shoreline retreat is interpreted as a proxy for elevated nutrient loading, while anthropogenically induced morphological alteration is used as a proxy for hydrodynamic stagnation. The resulting vulnerability maps provide spatially explicit outputs that highlight coastal segments at the highest ecological risk, offering a decision-support tool for local management and future monitoring [13], [14].

## 2 Data and methods

### 2.1 Study Area

Da Nang City (Fig. 1), located in Central Vietnam (15°15′–16°10′ N, 107°50′–108°20′ E), has over 90 km of diverse shoreline—including sandy beaches, estuaries, and rocky coasts—that are highly vulnerable to coastal erosion [10], [11].

The coastline is shaped by a tropical monsoon climate with typhoons, storm surges, river inflows (Han and Co Co Rivers), and longshore currents driven by the northeast monsoon [2].

Since 2004, rapid urbanisation and tourism development have intensified anthropogenic pressures, especially in Son Tra and Ngu Hanh Son districts, causing erosion in Nam O, Thanh

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Binh, and Hoa Hai and localised accretion near river mouths [10], [11].

These changes require long-term monitoring to support sustainable coastal management in the context of climate change and urban development.

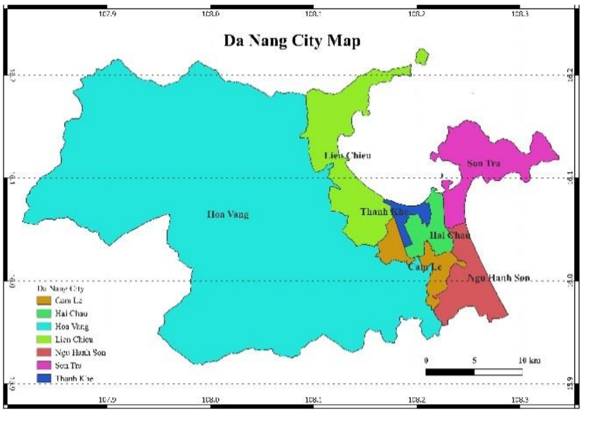


**Fig. 1.** Da Nang Map

## 2.2 Data and methods

This study integrated remote sensing techniques with automated geospatial processing by using the open-source Python library CoastSat. According to Vos et al., CoastSat is a validated and widely adopted tool for long-term shoreline change monitoring, known for its accuracy, reproducibility, and scalability [15], [16]. The library interfaces with Google Earth Engine (GEE) to retrieve and process satellite imagery from the Landsat and Sentinel-2 missions, offering a major advantage over traditional GIS software in terms of spatio-temporal coverage and automation.

To ensure analytical accuracy in assessing shoreline change in Da Nang (2004–2024), we compiled a multi-source dataset and applied automated geospatial processing with the CoastSat library. The workflow consisted of five main steps.

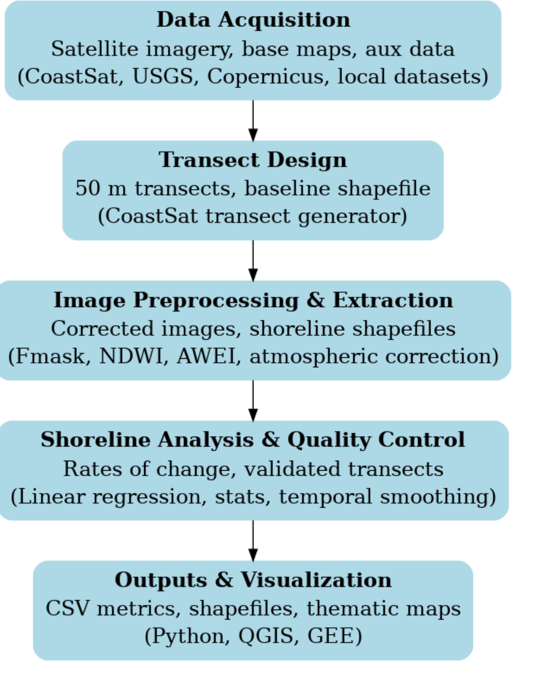


**Fig. 2.** General workflow of shoreline change analysis

### Data acquisition

Multi-temporal satellite imagery from Landsat (5 TM, 7 ETM+, 8 OLI, 9; 30 m, 16-day revisit) and Sentinel-2 MSI (10 m, 5-day revisit) was collected from USGS Earth Explorer and Copernicus Hub. Benchmark years (2004, 2009, 2014, 2018, 2023) were selected to represent long-term change. The year 2004 marks the beginning of rapid urban development along the Da Nang coast, coinciding with increased availability of Landsat 5 data. The year 2009 represents a mid-decade reference during accelerated tourism and infrastructure growth. The year 2014 coincides with post-typhoon recovery and significant shoreline interventions. The year 2018 captures the period following the expansion of large-scale coastal projects and provides an overlap between Landsat 8 and Sentinel-2 datasets for higher spatial resolution. Finally, 2023 was chosen as the most recent reference year, integrating the latest Landsat 9 and Sentinel-2 imagery, thereby providing an updated baseline for shoreline monitoring.

Supporting datasets included topographic and administrative maps, planning documents (land use and coastal zoning), environmental reports, meteorological-hydrological records (wind, waves, tides, and currents), and high-resolution images from Google Earth and UAV surveys.

**Transect design of study area**

The study area encompassed the entire coastal zone of Da Nang City, Vietnam. By using geographic coordinates, a baseline was established along the shoreline, from which transects were generated at regular 50-metre intervals and oriented perpendicularly. These transects served as reference points for detecting and analysing shoreline positions across time. CoastSat was used to automatically retrieve suitable satellite images (with <10% cloud cover) between 2004 and 2024, prioritising temporal consistency and image quality [17].

**Image preprocessing and shoreline extraction**

Once retrieved, imagery underwent standard preprocessing steps. Geometric correction was performed systematically by using the ground control and sensor metadata provided by USGS/ESA. Atmospheric correction (LEDAPS for Landsat and Sen2Cor for Sentinel-2) was applied when surface reflectance products were unavailable; otherwise, top-of-atmosphere reflectance data were retained. Cloud and cloud-shadow pixels were identified and masked by using the Fmask algorithm, and only scenes with <10% overall cloud coverage were retained, consistent with CoastSat's automated filtering. All images were then clipped to the study area extent to reduce computational load, and spectral normalisation was applied to minimise inter-sensor differences before shoreline extraction [18]. Landsat 7 ETM+ scenes were assessed for SLC-off (scan line corrector failure) artifacts by computing a per-scene gap mask and the gap fraction within a 200-m coastal buffer. Scenes with gap fraction >10% in the coastal buffer were excluded from shoreline extraction. For scenes with smaller gaps (≤10%), missing pixels were gap-filled using a multi-date median compositing approach (±60 days) prioritising same-sensor images; remaining small gaps were interpolated by using a 3 × 3 focal mean. We validated gap-filled results by visually inspecting a random sample (10%) and performing sensitivity tests with alternative thresholds (5% and 15%). Shorelines were extracted by using water indices such as NDWI (Normalised Difference Water Index) and AWEI (Automated Water Extraction Index), which differentiate land and water surfaces. To improve accuracy, especially for medium-resolution imagery, some researchers employed sub-pixel edge detection techniques [13]. Each extracted shoreline was then associated with specific transects and time stamps to construct a time series.

**Shoreline change analysis and quality control**

For each transect, the shoreline positions over time were analysed by using linear regression to estimate the average annual rate of shoreline movement (in metres per year). Statistical measures, such as standard deviation, confidence intervals, and the number of valid observations, were calculated to assess reliability [17]. Across all transects, the aggregated root mean square error (RMSE) of shoreline position was approximately ±10–15 m for Landsat-derived shorelines and ±5–7 m for Sentinel-2. Transects with irregular patterns or outliers were re-examined by using high-resolution Google Earth imagery or available field data for validation.

Error control was a critical step to ensure objectivity and data integrity. Transects showing

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significant deviations from surrounding trends or affected by clouds, tides, or wave interference were flagged and re-evaluated. CoastSat's built-in spatiotemporal filtering was used to eliminate noise, and temporal smoothing techniques (e.g., moving average) were applied to reduce local anomalies. All spatial datasets were standardised in terms of coordinate systems and formats to maintain consistency throughout the analysis.

**Output and visualisation**

The final outputs included shapefiles of shoreline positions, CSV files with calculated displacement metrics, and graphical visualisations such as time series plots and thematic maps. All processing was conducted in the Python environment, supporting automation, transparency, and reproducibility. The workflow can be easily adapted to other coastal areas or extended to future time periods with minimal modification.

**Software and processing tools:** A combination of open-source and proprietary tools was used for data processing and analysis. QGIS and ArcGIS facilitated spatial organisation and map layer integration; SNAP (Sentinel Application Platform) handled Sentinel-2 imagery preprocessing and NDWI analysis; Google Earth Engine (GEE) supported large-scale, cloud-based image processing; Python (with the CoastSat library) enabled precise shoreline detection and quantitative shoreline change analysis.

## 3 Results and discussion

### 3.1 Spatial patterns of shoreline change

**Shoreline extraction and temporal trends (2004–2024)**

The shoreline extraction process was carried out by using the open-source CoastSat library, in combination with multi-temporal satellite imagery from Landsat 5, 8, 9, and Sentinel-2. Shorelines were delineated with NDWI and AWEI spectral indices, along with sub-pixel edge detection algorithms, ensuring high precision in identifying the land-water boundary.

A set of sample images from the 2004–2024 dataset was illustrated in Fig. 3, including raw satellite scenes (left), classified land-water masks (center), and a pseudo-color image (right). These results confirm the method's consistency and accuracy across two decades, providing a robust foundation for long-term shoreline monitoring.

After shoreline extraction, the data were structured by using a system of transects — cross-sectional lines perpendicular to the baseline, spaced 50 metres apart. These transects serve as reference points for analysing shoreline displacement over time.

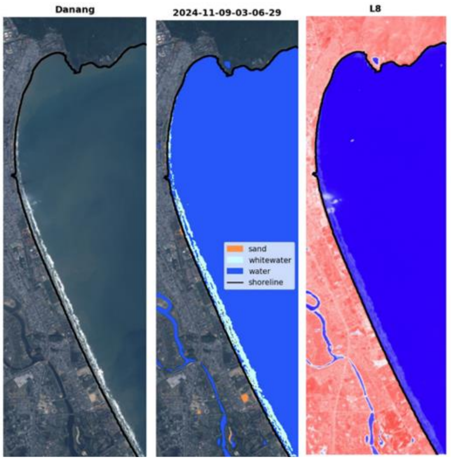


**Fig. 3.** Illustration of shoreline extracted from satellite imagery during the 2004–2024 period.

**Spatial analysis using representative transects**

For assessing spatial patterns in shoreline dynamics, over 100 transects were generated along the entire Da Nang coastline. Among these, three representative transects were selected for detailed analysis on the basis of their distinct geographic and land-use characteristics, as shown in Fig. 4. Transect 1 is located in southern Da Nang near the Quang Nam border, an area experiencing rapid urban expansion. Transect 2 lies along My Khe Beach, which is characterised with dense tourism infrastructure and high development intensity. In contrast, Transect 3 is situated on the Son Tra Peninsula, a relatively undisturbed ecological zone with minimal human activity, serving as a control site for natural shoreline processes.

Shoreline position data for each transect were analysed over the 20-year period (Fig. 5). The results reveal contrasting trends across the three representative transects. Transect 1 exhibited a significant shoreline retreat beginning around 2015, which is likely associated with intensified coastal development and human interventions in the southern area. In contrast, Transect 2 remained relatively stable throughout the study period, with only minor seasonal variations observed.

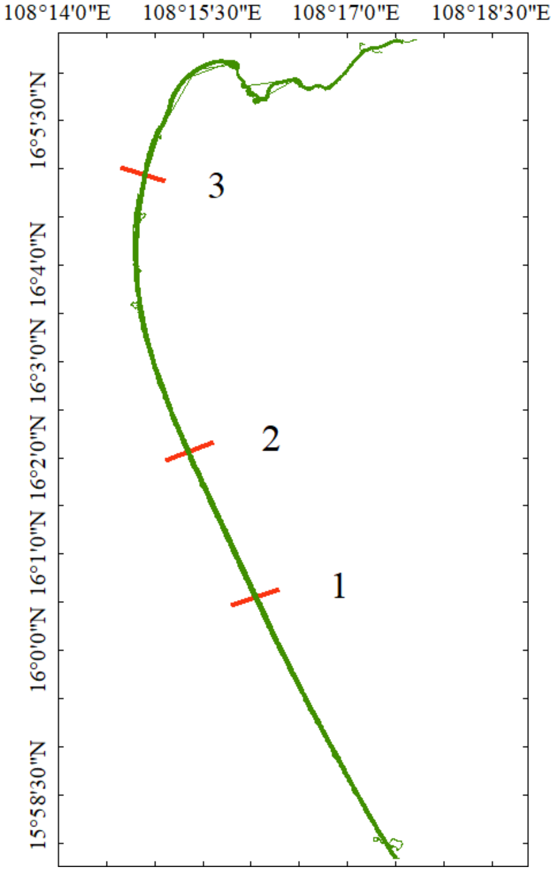


**Fig. 4.** Location of transects from South to North

Transect 3, located in a less disturbed ecological zone, demonstrated a gradual trend of shoreline accretion, likely driven by natural sediment deposition processes. Notably, all three transects showed relatively low variability from 2004 to 2015, followed by increased fluctuations in shoreline position from 2016 onward. Notably, all three transects experienced relatively low variability from 2004 to 2015, followed by increased fluctuations in shoreline position from 2016 onward. Part of this apparent increase can be attributed to the higher temporal resolution of available imagery after 2015, as Sentinel-2 data (10 m, 5-day revisit) began to complement Landsat imagery (30 m, 16-day revisit), thereby capturing short-term shoreline dynamics that may have been under-represented previously [16]. However, the trend is also consistent with intensifying natural and anthropogenic influences in Da Nang. For instance, the period after 2016 coincides with a sequence of strong typhoon seasons (e.g., Typhoon Damrey in 2017 and Typhoon Molave in 2020) as well as rapid coastal development projects such as land reclamation, resort construction, and port expansion [20], [21]. Together, these factors contributed to both episodic erosion and localised accretion, reinforcing that the post-2016 variability reflects genuine geomorphic responses rather than solely an artifact of improved satellite monitoring.

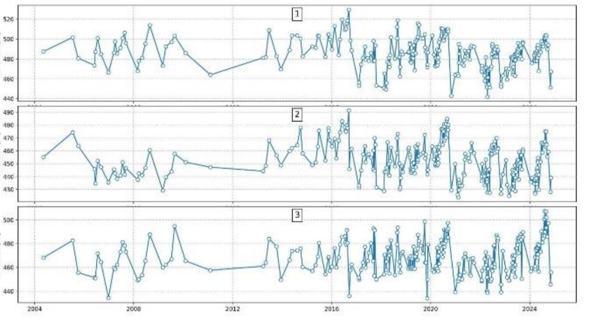

**Fig. 5.** Time series and shoreline distance graphs at transects 1, 2, 3

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For understanding tidal influence on the shoreline, Fig. 6 illustrates the time series of tidal levels from 2004 to 2024, with the grey-shaded area representing the continuous and periodic tidal fluctuations in metres. The tidal levels range from –0.8 m to +0.6 m, clearly reflecting the cyclical nature of tidal phenomena in the study area. This periodicity aligns with the typical semi-diurnal and diurnal tidal patterns observed along the Vietnamese coastline. The presence of distinct and regularly recurring peaks and troughs indicates high temporal stability, providing a reliable foundation for long-term shoreline change analysis [22].

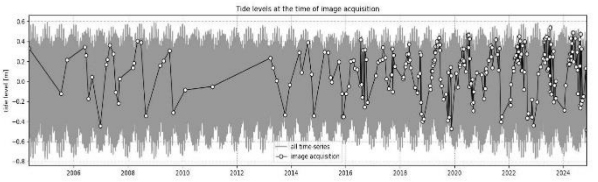


**Fig. 6.** Time series of tidal levels and corresponding tide heights (2004–2024)

Superimposed on the full tidal time series are circular data points connected through lines, representing the tide levels at the time of satellite image acquisition. These acquisition points are distributed across the entire tidal range, from low tide to high tide, indicating that satellite images were captured under diverse tidal conditions. This varied distribution enhances the representativeness and reliability of the satellite dataset while minimising tidal-induced errors in shoreline interpretation. Notably, from 2018 onwards, the frequency of image acquisitions increases significantly, largely because of the launch of newer Earth observation satellites such as Sentinel-2, which improve the temporal resolution of the dataset. This enables the construction of a more continuous and accurate shoreline time series. Furthermore, applying tidal-level correction methods to shoreline positions is essential to improving the precision of shoreline change assessments over time.

Post-correction results (Fig. 7) show that shoreline positions became more consistent and convergent across years, particularly during high-variation periods. This demonstrates the importance of tide normalisation for improving shoreline detection accuracy in long-term analyses.

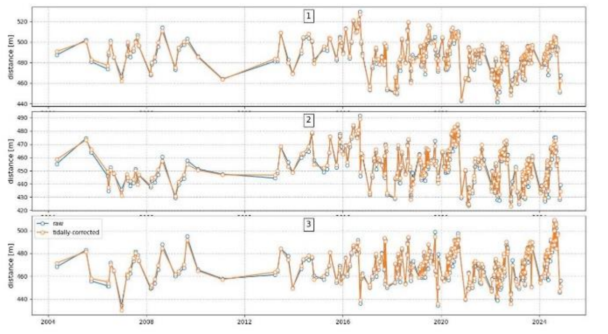


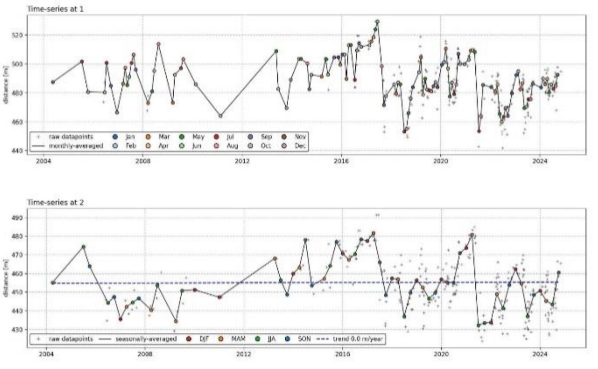
**Fig. 7.** Time series plots of shoreline positions at Transects 1, 2, and 3 after tidal correction

The charts in Fig. 7 highlight shoreline position changes over time at three distinct transects from 2004 to 2024 based on two data series: raw shoreline positions and tidally-corrected shoreline positions. The comparison reveals that, after tidal correction, the shoreline variation becomes more stable and consistent, particularly during periods of high tidal amplitude. This indicates that tidal correction significantly reduces errors caused by water level fluctuations, thereby providing a more accurate representation of erosion and accretion processes at each transect.

Furthermore, all three transects exhibit a marked increase in shoreline variability after 2016. This trend coincides with the increased frequency of satellite image acquisitions and may be associated with either natural coastal dynamics or anthropogenic influences within the study area.

### 3.2 Seasonal and temporal variability

Shoreline position data at the three representative transects reveal clear seasonal dynamics, strongly influenced by the monsoon regime. During DJF (winter, northeast monsoon) and SON (autumn, storm season), the shoreline consistently retreated landwards, reflecting the impact of stronger winds, higher wave energy, and frequent storm surges. In contrast, MAM (spring) and particularly JJA (summer, calm season) showed relative stability or slight accretion, most notably at the Son Tra Peninsula, where natural sediment deposition prevails.



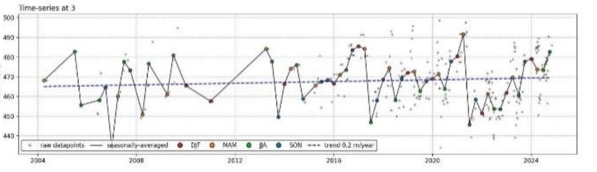


**Fig. 8.** Seasonal shoreline variation from 2004 to 2024

Fig. 8 illustrates the seasonal grouping of shoreline positions (DJF, MAM, JJA, and SON), showing stronger retreat during DJF and SON, while shoreline stabilisation or accretion dominates during JJA.

For the provision of a quantitative perspective, average shoreline change rates were calculated by season and by transect (2004–2024) (Table 1).

**Table 1.** Average seasonal shoreline change rates (m/year) at representative transects (2004–2024)

| Season | Transect 1 (South) | Transect 2 (Central) | Transect 3 (North) | Overall Mean |
|---|---|---|---|---|
| DJF | –1.3 ± 0.4 | –0.6 ± 0.3 | –0.2 ± 0.2 | –0.7 |
| MAM | –0.5 ± 0.2 | –0.2 ± 0.1 | +0.3 ± 0.2 | –0.1 |
| JJA | –0.1 ± 0.1 | +0.2 ± 0.2 | +0.5 ± 0.3 | +0.2 |
| SON | –1.0 ± 0.3 | –0.4 ± 0.2 | –0.1 ± 0.2 | –0.5 |

*Negative values indicate erosion; positive values indicate accretion. ± values represent one standard deviation (SD).*

The results reveal two key patterns. First, erosion is the most severe during DJF and SON, when shoreline retreat rates exceed –1.0 m/year at the southern transect (T1). These seasons coincide with high-energy waves from the northeast monsoon, generating oblique longshore currents that intensify sediment transport. The central transect (T2) also retreats during these periods, though at a lower rate, while the northern transect (T3) remains relatively stable, reflecting its more sheltered location. Second, shoreline stability or accretion occurs primarily during JJA with accretion rates of +0.5 m/year at T3, indicating the influence of calmer wave regimes and natural sediment deposition processes. Fig. 9 presents the monthly distribution of shoreline positions, further confirming that the largest fluctuations occur between September and January, coinciding with the northeast monsoon and storm surge season.

This seasonal contrast underscores the dual control of meteorological forcing and geomorphological setting: monsoon-driven winds and waves act as primary agents of erosion, while site-specific conditions such as sediment supply and human intervention modulate the magnitude of change. Statistically, erosion rates show significant positive correlations with wind speed

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($r$ = 0.62; $p < 0.01$) and significant wave height ($r$ = 0.71; $p < 0.01$), confirming the dominant influence of seasonal metocean dynamics on shoreline mobility.

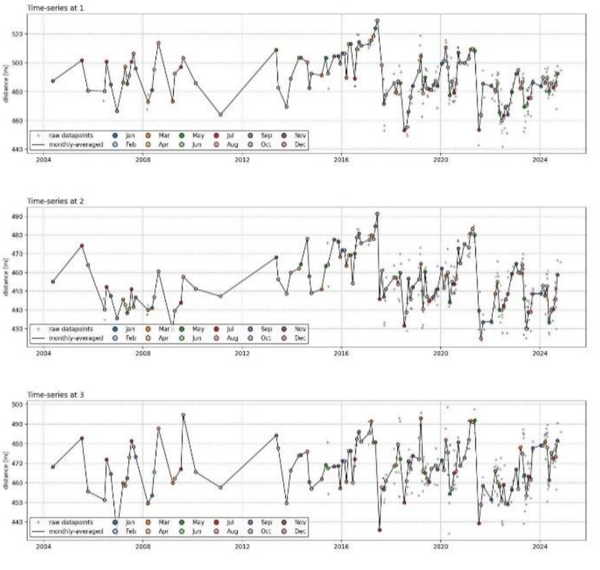


**Fig. 9.** Average monthly shoreline variation

Beyond physical processes, these seasonal variations also carry important ecological implications. During the monsoon and storm seasons, accelerated erosion enhances the flux of nutrient-rich sediments from land to sea, creating conditions favourable for eutrophication. When combined with storm-induced mixing and subsequent hydrodynamic stagnation in modified coastal zones, these processes substantially elevate the risk of harmful algal blooms. Conversely, the relative stability and slight accretion during the dry summer months may temporarily reduce nutrient loading, lowering baseline HAB risk.

The seasonal analysis demonstrates that the periods of greatest shoreline retreat (DJF, SON) also represent the periods of highest ecological vulnerability, reinforcing the role of shoreline dynamics as a spatial proxy for HAB risk assessment in central Vietnam.

### 3.3 Shoreline change and meteorological–oceanographic drivers

To strengthen the interpretation of shoreline dynamics, we compared shoreline displacement rates with available meteorological and oceanographic records (wind speed, wave direction, and tidal fluctuations) during 2004–2024.

*Wind speed and direction*. Periods of enhanced erosion, particularly at Transect 1 (southern Da Nang), coincided with higher mean wind speeds (>15 m/s) during the northeast monsoon (DJF season). Shoreline retreat rates in these months averaged –1.2 to –1.5 m/year, significantly higher than those in calmer months (–0.3 to –0.5 m/year).

*Wave regime*. Shoreline retreat was strongly associated with wave approach direction. Northeasterly waves during storm surges generated oblique longshore currents, intensifying sediment transport and accelerating erosion in southern sectors. In contrast, lower-energy southeasterly waves during JJA were correlated with stabilisation or slight accretion (+0.2 to +0.4 m/year).

*Tidal fluctuations*. Semi-diurnal tidal ranges (–0.8 m to +0.6 m) contributed to intra-annual shoreline variability. After tidal normalisation, the variance of shoreline position decreased by ~20–25%, confirming tides as a secondary but significant driver of short-term shoreline movement.

These results highlight that shoreline dynamics in Da Nang are not only shaped by anthropogenic factors but also tightly coupled with seasonal meteorological–oceanographic forcing. This underscores the combined influence of natural drivers and human-induced pressures on the observed coastal change.

### 3.4 Discussion

**Shoreline dynamics as a proxy for harmful algal bloom risk**

The results of the shoreline change analysis provide more than a physical assessment; they offer critical insights into the underlying drivers of ecological risk, particularly for harmful algal blooms. The observed dynamics at the representative transects can be interpreted as indicators of the two primary conditions required for HABs: nutrient enrichment and water column stability.

The pronounced erosion identified at Transect 1 and along the southern coast represents a significant pathway for nutrient loading into the marine environment [23]. This process, closely associated with rapid urban expansion, effectively transports land-based materials, including nutrient-rich topsoil, residual fertilisers from past land use, and pollutants from urban runoff. The constant influx of this material creates a state of eutrophication, supplying the nitrogen and phosphorus that are essential for algal growth and thereby increasing the baseline risk of a bloom event in these waters. The eroding coastline thus functions as a "source zone" for the fuel that powers HABs.

While Transect 2 at My Khe Beach showed overall stability, its location within a zone of intense tourism development presents a different kind of risk [24]. The shoreline here is heavily modified by infrastructure such as seawalls, ports, and other tourist facilities. Although these structures may prevent large-scale shoreline retreat, they alter local hydrodynamics and nearshore currents. This can create localised areas of poor water circulation. When combined with potential point sources of pollution common in high-tourism areas, such as wastewater outlets, these pockets of stagnant water can become high-risk "hotspots" for algal blooms, even in the absence of widespread erosion.

The gradual, natural accretion observed at Transect 3 on the Son Tra Peninsula serves as an important scientific baseline for an undisturbed system. However, in other areas where accretion may be artificially induced or influenced by coastal construction, it can pose a significant risk. Such accretion can lead to the formation of semi-enclosed coves or lagoons with restricted water exchange. These areas function as "incubation zones" for HABs. The reduced water circulation leads to longer water residence times, allowing nutrient concentrations to build up and water temperatures to increase, creating the perfect stable, warm, and nutrient-rich environment for algal cells to proliferate rapidly into a bloom [14].

The observed patterns in Da Nang are consistent with findings from other coastal regions in Vietnam and worldwide. For example, Tien et al. reported similar erosion-accretion dynamics in the Hau River estuary, where rapid urbanisation intensified shoreline retreat [8]. This reinforces the role of anthropogenic drivers across different geomorphic settings. International studies also corroborate these trends. Xu, analysing three decades of Landsat data for the Texas coast, demonstrated that systematic shoreline retreat is often linked with nutrient enrichment from land-based inputs, a mechanism comparable with our findings for southern Da Nang [13]. Similarly, Vos et al. highlighted the influence of ENSO-driven variability on shoreline evolution across the Pacific, underscoring the need for integrating climatic oscillations into long-term monitoring [11]. By situating the Da Nang case within these broader contexts, we can see that this study not only confirms site-specific drivers but also highlights the generalisable nature of using shoreline dynamics as a spatial proxy for ecological risk assessment.

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**Limitations and future research**

While this study establishes a strong correlative link, we acknowledge its limitations. The analysis failed to directly integrate *in-situ* water quality data (e.g., concentrations of nitrogen, phosphorus, and chlorophyll-a) with shoreline change metrics. Future research should aim to bridge this gap by combining remote sensing of shoreline dynamics with systematic water quality monitoring. Furthermore, hydrodynamic models should be employed to simulate how shoreline changes influence water residence time and circulation, thereby providing a more mechanistic understanding of algal bloom formation.

## 4 Conclusions

This study successfully constructed a multi-dimensional shoreline dataset, capturing the complex dynamics of Da Nang's coastline from 2004 to 2024. By applying an automated methodology on the basis of the open-source CoastSat library with multi-temporal satellite imagery and tidal correction, we established a consistent, objective, and high-precision framework for long-term shoreline monitoring. This approach not only enhanced the accessibility and replicability of the analysis but also proved to be an effective solution for regional-scale coastal research. The findings confirmed significant seasonal and spatial variability in shoreline behaviour, with shoreline retreat being most prominent during the monsoon seasons (DJF, SON) and accretion typically occurring in the dry seasons (JJA, MAM). Spatially, the analysis quantified a trend of slight accretion in northern sectors like the Son Tra Peninsula (+0.5 to +1.2 m/year) and notable erosion in southern areas (up to –1.5 m/year), and the results align with field observations and local reports.

However, the primary contribution of this research extends beyond the quantification of these physical changes. The study demonstrates that these shoreline dynamics serve as a direct spatial proxy for the underlying conditions that foster harmful algal blooms. The severe erosion observed in the southern sectors acts as a persistent pathway for land-based nutrient loading, fueling eutrophication. Simultaneously, the alteration of coastal morphology, whether through erosion or human-influenced accretion, creates the stagnant, hydrodynamically stable "incubation zones" necessary for algal proliferation. The integration of spatial analysis and field data thus provides a robust foundation not only for physical planning but also for assessing emergent ecological risks.

Ultimately, this research underscores the value of using remote sensing technologies to address complex coastal challenges amid rapid urban development and climate change. By re-contextualising shoreline change as an indicator of ecological vulnerability, we emphasise the urgent need for an integrated coastal management approach in Da Nang. Such a strategy must simultaneously address physical shoreline stability and the drivers of ecological degradation, such as nutrient pollution. By doing so, we can move towards more effective climate adaptation and disaster risk management that protects both the coastline and the health of its marine ecosystem.

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